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Coarse Gravel Transport in
Steep Mountain Streams

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Introduction

Coarse gravel transport was sampled in three steep mountain streams. Large wire baskets were suspended from instream weirs, allowing sampling for periods of hours to days, such that a large proportion of the moving sediment was captured. The objective of the field work was to develop a relatively accurate measure of coarse gravel transport rates, a difficult task using conventional field programs using hand-held samplers. The underlying motivation was to address the question of whether coarse gravel transport in steep streams is predictable. Predictability can be defined in different ways. At a minimum, predictability requires that a consistent relation exist between the bed composition, the flow, and the transport. The unusual sampling procedure used in this study was intended to measure transport with sufficient accuracy to evaluate such a relation. At a higher level, predictability requires a general relation that can be used in a consistent approach for prediction. Wilcock (1997) proposed a calibrated methodology for predicting transport rates in gravel-bed rivers. This method was developed using observations from streams with smaller grain size and gentler slopes. This report evaluates the applicability of the method to steep streams ($>2\%$) with coarser grain sizes ($D_{50} > 32$ mm, maximum grain size > 256 mm).

A variety of reasons have been proposed for why coarse sediment might not be predictable. If, for example, coarse sediment were essentially immobile, the observation of a grain in motion would be more a matter of chance than a consistent function of the flow and bed composition. Such might be the case, for example, if coarse sediment in a steep stream bed were a relict of Pleistocene sediment supply or restricted to local hillslope sources.

It is difficult to use conventional hand-held samplers to establish a transport relation for coarse grains in steep streams. Part of the problem is simply that hand-held samplers are smaller than the coarse sizes in some streams. Another part of the problem is the size of typical samples. If a 5 m wide stream were sampled with a typical 3-inch sampler, and 20 one-minute samples were collected in a one hour period, approximately one-half of one percent of the transport would be sampled. Given that even very active transport of coarse sediment has been demonstrated to be episodic, with grains spending more time at rest than in motion, it is difficult to establish any consistent trend using such a small sample. The approach used here—using open baskets capable of catching all sizes in the bed, and sampling a large fraction of the transport (up to $\approx$ one-half) for periods of hours to days—provides sufficient samples to evaluate whether a consistent relation exists.

Even with the advantage of instream structures from which baskets could be hung, accurate sampling coarse sediment transport rates is difficult and the field campaign was only partially successful. At one location, East St. Louis Creek, the sampling worked exceedingly well and a very good estimate of the variation of transport with discharge was developed. At other locations, a combination of sampling problems and site problems produced data of limited use.

This report describes the field campaign, presents the transport data, compares these data with the quantity of sediment cleaned out from weir ponds on two of the streams, and evaluates a calibrated approach for developing sediment rating curves.

The Streams

Two streams, East St. Louis Creek and Fool Creek, are located in the Fraser Experimental Forest, Colorado. The hydrologic and transport characteristics of these streams have been previously discussed by Troendle et al. (1996), Wilcox, et al. (1996), Troendle and Olsen (1994), and Leaf (1970). A summary of the drainage area and channel characteristics is given in Table 1.

Table 1. Study Streams	Drainage Area (ha)	Slope	Width (m)	D ₅₀ (mm)	D ₉₀ (mm)
East St. Louis Creek	803	0.068	2.8	36	200
Fool Creek	289	0.047	2.1	na	na
Coon Creek	1613	0.031	5.6	70	230
East Fk. Encampment River	911	0.038	4.2	38	150

Transport sampling was initially conducted at two locations on East St. Louis Creek. A single basket was attached to an abandoned concrete V-weir that captured all of the flow and transport in the channel. This installation failed because a sufficiently tight seal could not be established between the basket and the weir and an undetermined amount of sediment was able to pass through the intervening gap. Data collected at this site were not analyzed.

At a second location on East St. Louis Creek, transport was captured in two wire-mesh baskets suspended at the upstream lip of a weir pond. This sampling arrangement worked very well. The baskets were 0.3 m deep, 0.6 m in the downstream direction, 1.2 m in the cross-stream direction, and sampled approximately one-half of the active transport width entering the pond. The wire mesh opening was 25 mm; transport of finer grains was not sampled. Samples were collected during Spring runoff in 1996 and 1997 (Table 2). Sample duration varied between 1.3 hr and 99 hr. More than 90% of the samples were longer than 3 hr and the cumulative sample duration was 1817 hr (Table 3). The return period of peak runoff in 1997 exceeded three years. USFS personnel clean sediment from weir pond each year, removing sediment down to a hard clay pan at the base of the pond. The sediment is placed in piles next to the pond. The coarse component of the pond was measured in 1996 and 1998 by passing the pond catch through the one inch mesh of one of the wire baskets. The coarse grains were then sorted by 1/2 ϕ size class. All grains coarser than 45 mm were counted and a volumetric subset of grains in the 25-32 mm and 32-45 mm size classes was also counted. The annual load from the 1995 cleanout was also

estimated, although there is less certainty in the integrity of the pile and its composition. Runoff in 1995, 1996, and 1997 was relatively large, with peak flows exceeding $1.0 \text{ m}^3/\text{s}$ each year. Total runoff and peak discharge in 1998 was much smaller (Figure 1).

Table 2. Summary of Sample years	E. St. Louis Ck.	Fool Ck.	Coon Creek
Basket Data	1996,1997	1996,1997	1997
Pond Data	1995, 1996, 1998	none	1997, 1998

Table 3. Summary of Basket Samples		
(a) East St. Louis Creek	Sample Duration (min)	Total Sample (kg)
1996	620	43
1997	1,198	359
Total	1,817	402
(a) Coon Creek	Sample Duration (min)	Total Sample (kg)
1996	307	29
1997	790	102
Total	1,097	131

Transport on Fool Creek was sampled with a basket attached to an abandoned rectangular concrete weir. All flow and transport passed through the weir and into the basket. Although the design appeared to be effective in use, a number of sampling problems emerged that cause the data to be of limited use. Flow emerging from the weir obscured the seal between the basket and the weir wall, making it difficult to assure a tight fit. The basket was rotated out of the flow for cleanout, a procedure which resulted in some loss of sediment out of the lower end of the basket. Finally, analysis of the transport samples indicates that there was an upper limit to the quantity of sediment that could be efficiently trapped in the basket. Above this limit, sediment may have been removed from the basket by the intense flow. Samples were collected during Spring runoff in 1996 and 1997 (Table 2). Runoff in 1996 and 1997 was relatively large, with peak discharges exceeding approximately $0.5 \text{ m}^3/\text{s}$ (Figure 2). Sediment transport in Fool Creek is trapped in a pond that is not cleaned out annually. Although annual surveys of the pond surface are made, there is no basis for determining the size content of the annual load.

Transport sampling was also conducted on Coon Creek, located in the Medicine Bow National Forest in Wyoming. Transport was sampled with two wire baskets in an arrangement similar to

that on East St. Louis Creek, although without the same level of effectiveness. Pond depth at Coon Creek is smaller and deposition at the upstream end of the pond interfered with placement of the baskets. In 1996, deposition prior to the first field visit was sufficient that only one basket could be installed and its seal with the upstream sill was not always certain. Samples collected in both baskets during a six-day field visit in 1997 were continuously monitored and were more successful. The sediment removed during the annual pond cleanout in 1997 and 1998 was sampled as the cleanout occurred. Approximately one-third of the pond sediment was screened through the one-inch wire mesh and the coarser grains were sized at $1/2\phi$ intervals and counted. Runoff in 1996 and 1997 was relatively large, with peak flows exceeding $3.0 \text{ m}^3/\text{s}$ in 1996 and $4.0 \text{ m}^3/\text{s}$ in 1997 (Figure 3).

Transport sampling was also attempted on the East Fork Encampment River, immediately adjacent to Coon Creek. The sampling arrangements were nearly ideal, with a layout and effectiveness similar to that at East St. Louis Creek. Unfortunately, there was almost no sediment to sample. Approximately 50 m upstream of the pond and just downstream of a section where flow and transport samples have been collected in previous years (Wilcox et al., 1996), the channel passes through a tight double bend. Several trees have fallen into the channel at the bend, causing a large gravel bar to deposit. Almost no sediment was delivered to the weir pond in 1996, 1997, and 1998, indicating that virtually all of the bed-material transport was trapped in this bar.

Transport Observations

Sediment trapped in the wire baskets was removed, sorted through a gravelometer into $1/2\phi$ fractions and the number of grains in each fraction was counted. Sample duration, peak discharge during each sample period, and the grain count are given in the appendix of this report. Conversion to mass was made assuming a spherical grain shape and a grain density of 2650 kg/m^3 .

Runoff on these streams is dominated by snowmelt. Diurnal fluctuations in discharge are regular, but relatively small (typically 5%-15% of peak daily discharge; Figures 1, 2, and 3). The transport information is presented here in terms of the peak discharge during each sample period. The influence of fluctuating discharge on transport rates is discussed in a later section. Most commonly, transport samples encompassed a single daily hydrograph. On some occasions, transport was sampled separately during the trough on the daily hydrograph, at which time the discharge variations are relatively small. On a few occasions, primarily toward the end of the runoff period as transport rates dropped to small values, the baskets were cleaned only after several days. The transport data presented here is distinguished according to whether the sample corresponds to a single daily hydrograph ("peak"), a hydrograph trough ("trough"), or multiple daily hydrographs ("multi-peak").

The mass of sediment samples collected on East St. Louis Creek is given in Figure 4 for individual size fractions and for all fractions combined. The data are quite coherent and show a

consistent increase with flow strength. Scatter at small discharges and transport rates is associated with samples containing one, two, or three grains in the 25-32mm or 32-45mm size classes. Given that the duration for these samples was at least several hours and typically one or more days, a sample containing only a few grains of these sizes represents an exceedingly small transport rate that falls below the resolution of even basket samplers.

The East St. Louis Creek transport samples are expressed as a transport rate per unit stream width in Figure 5. The variation of transport rate with discharge is stunningly coherent. With the exception of the six samples containing one to three small grains, the transport rates fall within a band that is remarkably tight for field observations of coarse sediment transport. Note that distorted axes are used in Figure 5, with the discharge axis stretched by roughly a factor of five in order to provide some distinction among the data. If a true scale log-log plot were used, the data trend would be so tight as to obscure many of the observations. 1996 and 1997 data fall on the same trend, as do single and multiple peak observations. There is some suggestion that observations taken during the hydrograph trough fall slightly to the left of the other data, although the narrow separation and small number of trough samples do not allow a demonstration of significance.

The mass of sediment samples collected on Fool Creek is given in Figure 6 for individual size fractions and for all fractions combined. There is not a coherent variation in sample size with discharge, as evident at East St. Louis Creek. There appears to be an upper limit for sample size of the order 10 kg, suggesting that sediment was lost from the basket once the sample reached this size. Loss could have occurred during sampling or during cleanout. Scaling the transport samples by sample duration and channel width adds some coherence to the trends (Figure 7).

The mass of sediment samples collected on Coon Creek is given in Figure 8 for individual size fractions and all fractions combined. The remote location of the site and installation problems prevented development of a sampling record comparable to the two streams in the Fraser Experimental Forest. The most reliable observations are four samples of approximately 24 hour duration collected during a one-week field visit in 1997. More uncertainty must be assigned to the 1996 samples, which used a single basket with uncertain placement and the multi-peak samples, which typically sampled for a duration of one week.

Fractional Transport Rates

Total transport rates for East St. Louis Creek are given in Figure 10, along with the transport rates for each individual size fraction. There is no difference evident among the transport rates of the different size fractions, with all following the same coherent trend. Even the coarsest size fraction in motion, 90.5-128 mm shows a consistent increase with discharge, indicating hydraulic control of its transport rate. The exponent of a power law fit between transport rate and discharge is very steep, of order 10, as is typical for such small transport rates. Uncertainty in the value of this exponent increases with grain size, primarily as a function of a reduction in sample size with increasing grain size.

Variations in Discharge

The diurnal fluctuations in discharge typical of mountain streams with snowmelt regimes poses a problem for developing a sediment rating curve from sampled data. Samples are often collected over a period during which discharge changes, such that a simple correlation between discharge and transport cannot be made. To investigate the influence of variable discharge on observed transport rates, a sediment rating curve was developed for instantaneous flow values. This was done for East St. Louis Creek only, for which high quality transport data were available. Based on the consistency of the relation with peak discharge, a power function was assumed for the instantaneous relation. The trial power function was multiplied by the instantaneous discharge and its duration and summed over the period associated with each basket sample. The values of the coefficient and exponent were varied until an optimum was found that minimized the sum of the squared deviations between predicted and observed transport (Figure 11). This solution also minimized the ratio between predicted and observed for the cumulative transport in all basket samples.

The resulting power function was nearly identical to that for transport rate as a function of the peak discharge Q_{max} (Figure 10). The instantaneous rating curve falls slightly to the left of the Q_{max} curve, because, for a particular transport sample, the instantaneous discharge producing the transport will always be slightly less than the peak discharge during the sampling period. The similarity between the two sediment rating curves is due to two factors. First, the daily fluctuation in discharge was not particularly large. Only 10 of the 74 samples had a daily fluctuation of more than 20%. Second, the very steep slope of the rating curve means that most of the sediment moved during a sample period will occur near the peak flow. For example, the daily discharge fluctuation on 6/19/97 was 10.6 cfs, or 25.7% of the daily peak. Even for this relatively large fluctuation, calculation with the instantaneous sediment rating curve indicates that 88% of the transport occurred during the period when the discharge was within 10% of daily peak flow. For 34 of 74 samples, daily discharge varied less than 10% from its peak value. For the remaining flows, most of the transport occurred at discharges within 10% of daily peak.

The distinction between the two sediment rating curves is quite subtle and would be unlikely to be apparent using data collected with conventional hand-held samplers. This suggests that sediment rating curves developed from hand-held samplers can use the peak discharge during the sample period. In almost any imaginable case, the discharge fluctuations during a hand-held sampling traverse would be much smaller than the discharge fluctuations sampled in this study, the influence of which is apparently minor.

Application of a Calibrated Transport Model

In addition to the existence of a consistent relation between flow and transport rate, predictability requires the development of a consistent or generalizable model or method of prediction. Studies from streams of gentler gradient have demonstrated that general transport formulas do exist, although Wilcock (1997) suggested that the input typically available for prediction is sufficiently

sparse that a large degree of uncertainty is typically associated with predictions of transport rate. Accordingly, he proposed a calibrated approach for predicting transport rates in mountain rivers as an alternative to predictions from formulas or from a sampling campaign. The former are notoriously inaccurate; the latter require a large effort and may still not achieve acceptable accuracy. The alternative approach can be based a few observations of small transport rates, which are used to calibrate a transport formula in an approach that can provide a superior combination of accuracy and effort and substantially reduces flow scaling error. Wilcock (1977) developed the method using transport observations from four streams and one flume, all with exceptionally well measured transport rates. All of these streams have lower slopes, finer grain size, and larger depths compared to the steep and complex flow in the mountain stream studied here. As part of this evaluation of the predictability of transport in steep, coarse streams, it is useful to evaluate the applicability of the calibrated transport model to these new data.

In developing the calibrated approach, Wilcock (1997) demonstrated that grouped sand and gravel transport rates collapse about two common relations (one for sand, one for gravel) when the bed shear stress is scaled by an empirically defined reference shear stress for the sand and gravel. Reference shear stresses (Parker et al., 1982; Wilcock, 1988) for the sand τ_{rs} and gravel τ_{rg} were calculated as the value of shear stress producing the reference transport rate of $W^* = 0.002$ where

$$W^* = \frac{(s-1)gq_{bi}}{f_i \rho_s (\tau/\rho)^{1.5}} \quad (1)$$

s is ρ_s/ρ , ρ_s is sediment density, ρ is fluid density, g is acceleration of gravity, f_i is the proportion of fraction i in the bed, q_{bi} is transport rate in units of mass per unit width and time, and the subscript i represents either the sand or the gravel fraction.

In addition to demonstrating an acceptable collapse about a common trend, a transport model, in order to be general, must demonstrate a consistent and plausible basis for the values of essential scaling parameters, in this case, τ_{ri} . Values of dimensionless reference shear stress

$$\tau_{ri}^* = \frac{\tau_{ri}}{(\rho_s - \rho)gD_i} \quad (2)$$

were shown to vary consistently with sand content between standard values at the limits of clean sand and gravel (Wilcock, 1998). In the present case, only coarse gravel transport was measured and the calibrated approach is applied to sizes coarser than 25 mm.

A calibrated estimate of transport rate requires specification of a transport function. Wilcock (1997) found that the Parker (1979) transport relation

$$W_i^* = 11.2 \left(1 - 0.8531 \frac{\tau_{ri}}{\tau} \right)^{4.5} \quad (3)$$

provides a good fit to the grouped gravel transport rates for four streams and one laboratory sediment. This relation is very similar in form to the Einstein bed-load curve and has been found

to represent gravel transport well in many streams. Most gravel transport data falls in the range above the reference transport rate of $W^* > 0.0025$, including the grouped data used by Wilcock (1997). In some cases, however, particularly in steep streams, transport rates may be much smaller than this reference transport rate. Based on the laboratory results of Proffitt and Sutherland (1983) and Paintal (1971), Parker (1990) found that the following relation

$$W_i^* = 0.0025 \left(\frac{\tau}{\tau_{ri}} \right)^{14.2} \quad (4)$$

provided a superior fit for small transport rates. The values of the two functions match at $\tau/\tau_{ri} = 1$; (3) is used for $\tau/\tau_{ri} > 1$ and (4) for $\tau/\tau_{ri} < 1$.

The input needed to develop a sediment rating curve are a rating curve for mean section velocity and measured sand and gravel transport rates. A remarkable feature of the calibrated transport method (Wilcock, 1997) is that the sand and gravel grain sizes are not needed, as long as τ_{rs} and τ_{rg} are found from transport samples. A characteristic grain size is needed to estimate skin friction in the approach given here, although it will be shown below that the final transport estimate does not depend strongly on the choice of grain size.

Three steps are required to develop the rating curve: a drag partition to determine skin friction, specification τ_{rg} (and τ_{rs} , if sand transport is being predicted), and calculation of the rating curve from the appropriate transport relation.

In order to use a transport relation based on τ , it is necessary to determine the skin friction or grain stress driving the transport. This calculation is notoriously difficult, particularly in steep gravel-bed streams, and is an important source of error in formula predictions of transport rate. Wilcock (1996) demonstrated that the most precise estimate of local stress is achieved using the flow depth and depth-averaged velocity in a flow resistance type relation, because these variables can be measured with more accuracy than some others, like energy slope and near-bed velocity. A similar argument is likely to apply for the section averaged stress, wherein the mean skin friction stress is estimated as a function of mean velocity and flow depth, both of which can be estimated with reasonable accuracy. A suitable relation is the power approximation to the Keulegan log profile;

$$\frac{U}{u_*} = 8.1 \left(\frac{h}{k_s} \right)^{1/6} \quad (5)$$

where U is mean flow velocity, h is flow depth, u_* is the bed shear velocity equal to $\sqrt{ghS}$ and k_s is grain roughness. To estimate grain stress, $k_s = 2D_{65}$, where D_{65} is calculated relative to the size distribution of transportable sediment (essentially the argument behind the approximate drag partition of Einstein (1950)). Solving (5) for h and substituting in $\tau = \rho ghS$, a dimensional relation for τ is obtained

$$\tau = 16.2(SD_{65})^{1/4}U^{3/2} \quad (6)$$

where τ is in Pa, U is in m/s, and D_{65} is in mm. Precision in values of S and D is not particularly important because they are present in (6) only to the power of $1/4$. More importantly, when transport observations are used to calibrate the transport estimate, one value of τ (τ_{ri}) is determined from the transport observations rather than the flow resistance relation. Therefore, the role of the stress estimate in (6) is limited to determining the variation of τ with Q , for which purpose the constants in (6) essentially cancel. This can be demonstrated approximately by using (6) to estimate τ at one flow from a known value of τ at another flow. Writing (6) for each flow and taking the ratio leads to

$$\tau_2 = \tau_1 \left(\frac{U_2}{U_1} \right)^{3/2} \quad (7)$$

Values of τ_{ri} and the sediment rating curve can be determined in one straightforward computational step. Measured transport rates are plotted as a function of discharge. For a range of discharge spanning the observations and extending to higher flows, U is found from the velocity-discharge curve, τ from (6), and q_b from (3) or (4) as appropriate. This transport relation is superimposed on the measured data and the value of τ_{rg} is adjusted to fit the transport function to the measured data.

The calibrated approach is illustrated here using transport observations from East St. Louis Creek and Coon Creek. These streams provide a good test of the applicability of this calibrated approach. Roughness and skin friction are difficult to estimate for such streams, making prediction from a transport formula highly uncertain. Flow and transport on such streams are also complex and difficult to measure in detail, emphasizing the advantage of an integral approach based on long duration samples. Discharge observations were used to develop a simple power function between discharge and mean velocity, which was used with (6) to calculate τ for different values of Q .

Application of the calibrated approach is demonstrated in Figure 12 for East St. Louis Creek. The gravel rating curve is based on (4) with τ_{rg} adjusted to provide the fit. Although the data in Figure 12 are sufficient to define an empirical sediment rating curve, the position of the curve (the value of τ_{rg}) would be well constrained by any reasonable subset of the transport data. Any choice of a half-dozen points spanning the range of discharge would yield essentially the same position of the fitted curve (i.e. the value of τ_{rg}). The value of τ_{rg} corresponds to Shields number of $\tau_{rg}^* = 0.039$ for D_{50} of the bed surface, which is within normal range of values observed in the field and very close to the comparable values based on high quality transport observations (Parker, 1990). This consistency provides confirmation of the transport samples and application of the calibrated transport prediction to a very steep stream with coarse sediment.

A simple indication of error associated with an uncalibrated formula is indicated on Figure 12 by showing the predicted transport using an identical analysis, except that the value of τ_{rg}^* is specified without benefit of the transport data, using values of $\tau_{rg}^* = 0.03$ and $\tau_{rg}^* = 0.06$, which bound the range commonly reported approximately bound typical range observed. At these low transport rates, a two-fold uncertainty in τ_{rg}^* (which could just as well be a two-fold uncertainty in estimating skin friction) is associated with a more than four order-of-magnitude difference in transport rate.

The calibrated transport prediction is applied to Coon Creek in Figure 13. The curve is fitted to the four single-peak observations in 1997, which are of the transport observations of highest quality. The gravel rating curve was based on (4) and τ_{rg} adjusted to provide the fit shown on Figure 13. This value of τ_{rg} corresponds to a Shields number of $\tau_{rg}^* = 0.043$ for the D_{50} of the bed surface, which is again within normal range of values observed in the field and very close to the value determined for East St. Louis Creek. This consistency provides further confirmation of that transport of coarse sediment in steep stream is predictable using general methods.

Comparison with Pond Samples

Annual sediment cleanout of the ponds at East St. Louis Creek and Coon Creek allow a separate check on the transport rates observed with the basket samples. The estimated annual load of fractions coarser than 25 mm are given in Figures 14 and 15. Grains finer than 45 mm were not sampled in 1995 at East St. Louis Creek. Based on a comparison with the cumulative size distribution for the pond sediment reported for 1993, the proportion of sediment coarser than 45 mm reported for East St. Louis Creek was greater in 1995, 1996, and 1998 (Figure 14). This difference may be due largely to the more comprehensive approach to measuring coarse sediment in this study, which included measurement of all grains coarser than 45 mm, as opposed to periodic sampling in the standard pond cleanout procedure. For Coon Creek, the coarse end of the pond size distribution in 1997 and 1998 straddles that reported for 1993 (Figure 15). The reduced proportion of the coarsest grains in 1998 may be attributed to the very small discharge (Figure 3).

The cumulative basket catch and pond sediment is given in Table 4 along with values calculated using the sediment rating curves shown in Figures 12 and 13. Comparison of calculated and observed is within a factor of three for the basket catch. Discrepancy between calculated and observed is somewhat larger for the seasonal pond sediment, with a close match for Coon Creek in 1997, a difference of a factor of 4 for East St. Louis Creek in 1996, and larger discrepancies at both sites for the lower flows in 1998. The difference at Coon Creek may be partly due to a deeper excavation of the pond sediment in that year; final survey data are not available at this point to confirm this. Discrepancy between calculated and observed pond sediment may also be attributed to error in estimating the volume of pond sediment and to deviation between observed and predicted in the lower portion of the sediment rating curve.

Table 4 Comparison of cumulative sediment transport in baskets and pond, compared to amount calculated from Qmax sediment rating curve

	Basket Catch		Season	
(a) East St. Louis Creek	Observed	Qmax Sediment Rating Curve	Observed	Qmax Sediment Rating Curve
1995	-	-	356 (>45 mm)	591
1996	43	41	520	114
1997	359	287	-	582
1998	-	-	176	0.087
(b) Coon Creek	Observed	Qmax Sediment Rating Curve	Observed	Qmax Sediment Rating Curve
1996	29	14.2	-	3560
1997	102	292	17,329	24,032
1998	-	-	1,072	285

Conclusions

Transport samples of sediment coarser than 25 mm were collected on three steep streams. Transport observations on one, East St. Louis Creek, are exceptionally coherent, demonstrating that a consistent relation exists between discharge and transport of coarse sediment in a steep mountain stream. This is the first prerequisite for developing a general approach to estimating sediment load in these streams. The transport rate of this coarse sediment is controlled by the flow rate in the channel. Transport of material up to 128 mm or $\approx D_{80}$ of the bed surface size distribution was shown to vary in a consistent and common relation with discharge. Transport observations made on Fool Creek appear to have been degraded by a problem with sample loss, preventing the demonstration of a clear relation between transport rate and discharge. A smaller number of samples were collected on the third stream, Coon Creek.

The measured transport rates closely fit a transport model developed from observations on gentler streams. On both East St. Louis Creek and Coon Creek, the calibrating parameter for the transport model, the reference shear stress τ^*_{rg} , corresponds closely to a standard values observed in the field and in the laboratory. This consistency provides confirmation that transport in steep streams is predictable and that the calibrated transport method developed for gentler streams may be applied to steep streams with coarse sediment.

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Wilcox, M.S., C.A. Troendle, and J.M. Nankervis, 1996. Bedload transported in gravelbed streams in Wyoming, *Sixth Interagency Sedimentation Conference*, Las Vegas.

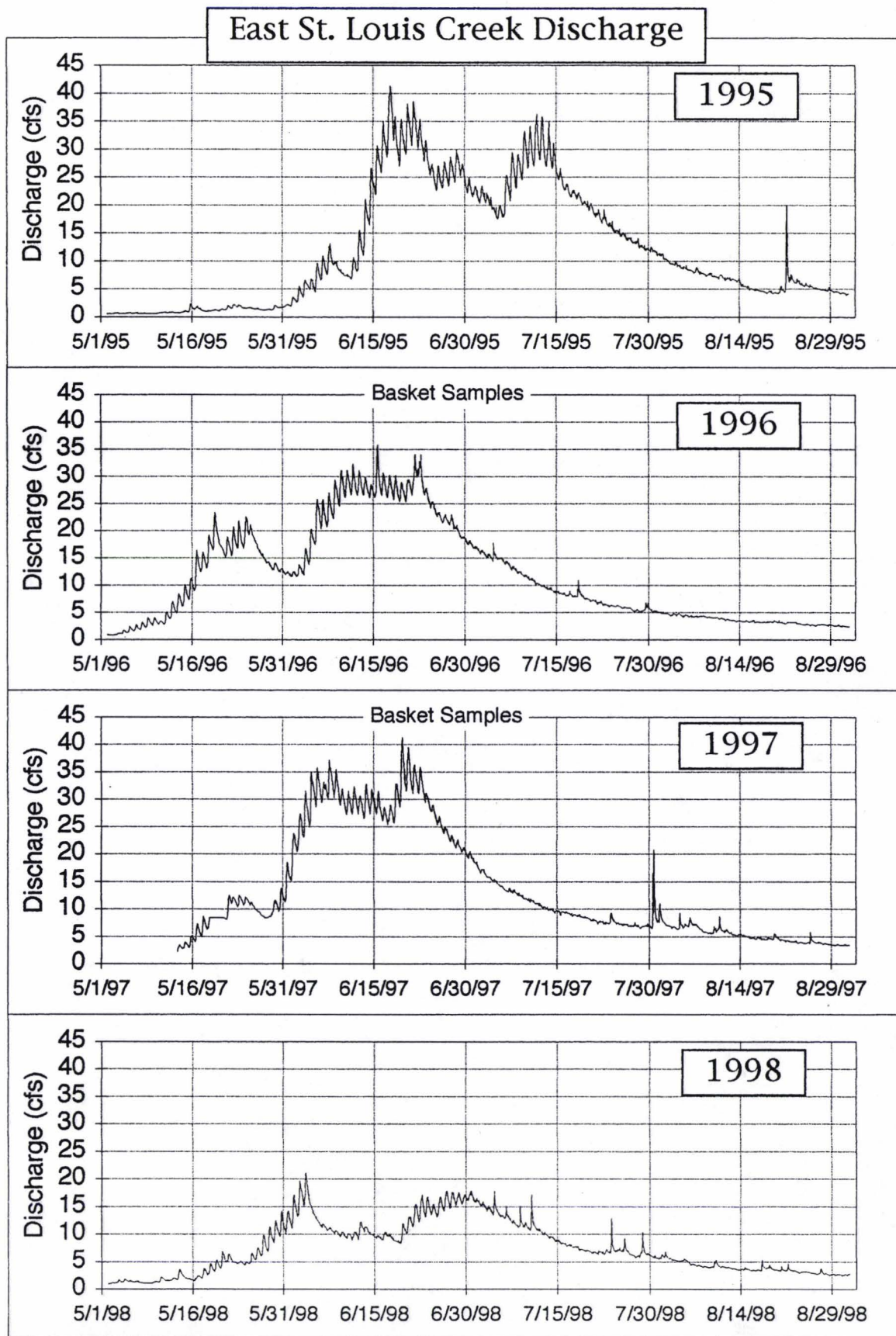


Figure 1. East St. Louis Creek, Hydrographs 1995-1998.

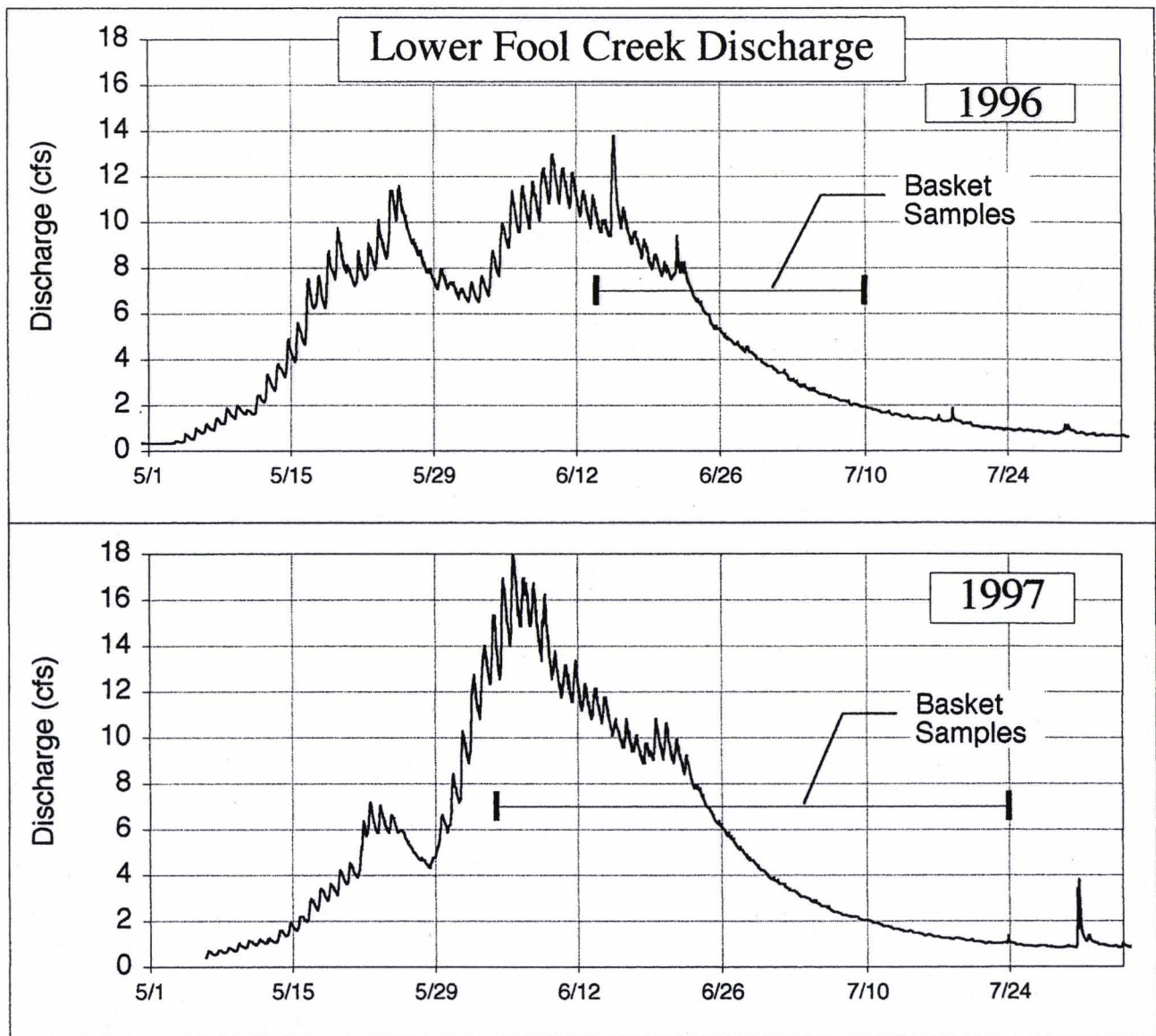


Figure 2. Fool Creek, Hydrographs 1996 and 1997.

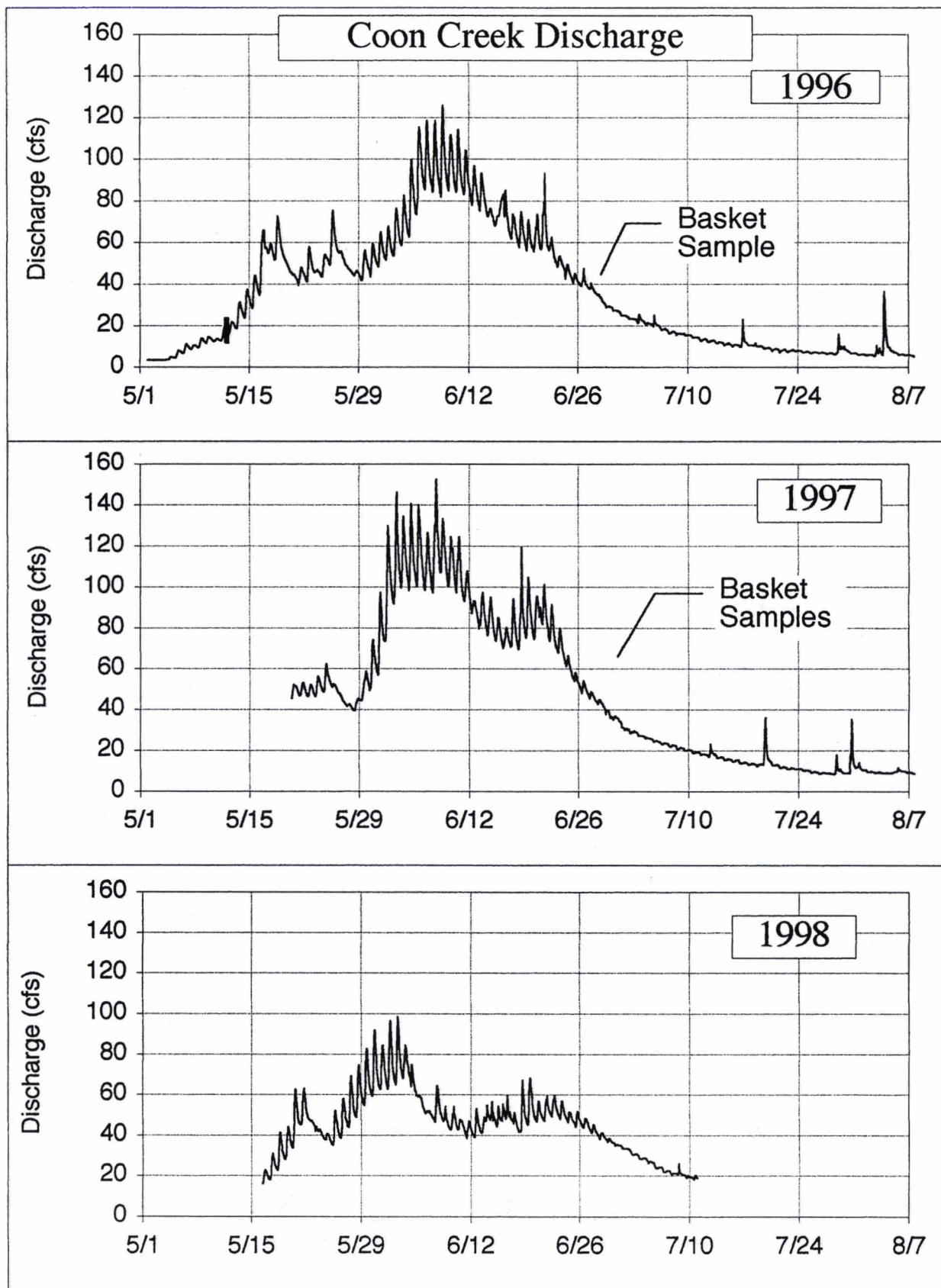


Figure 3. Coon Creek, Hydrographs 1996 - 1998.

East St. Louis Creek Basket Samples @ Weir Pond

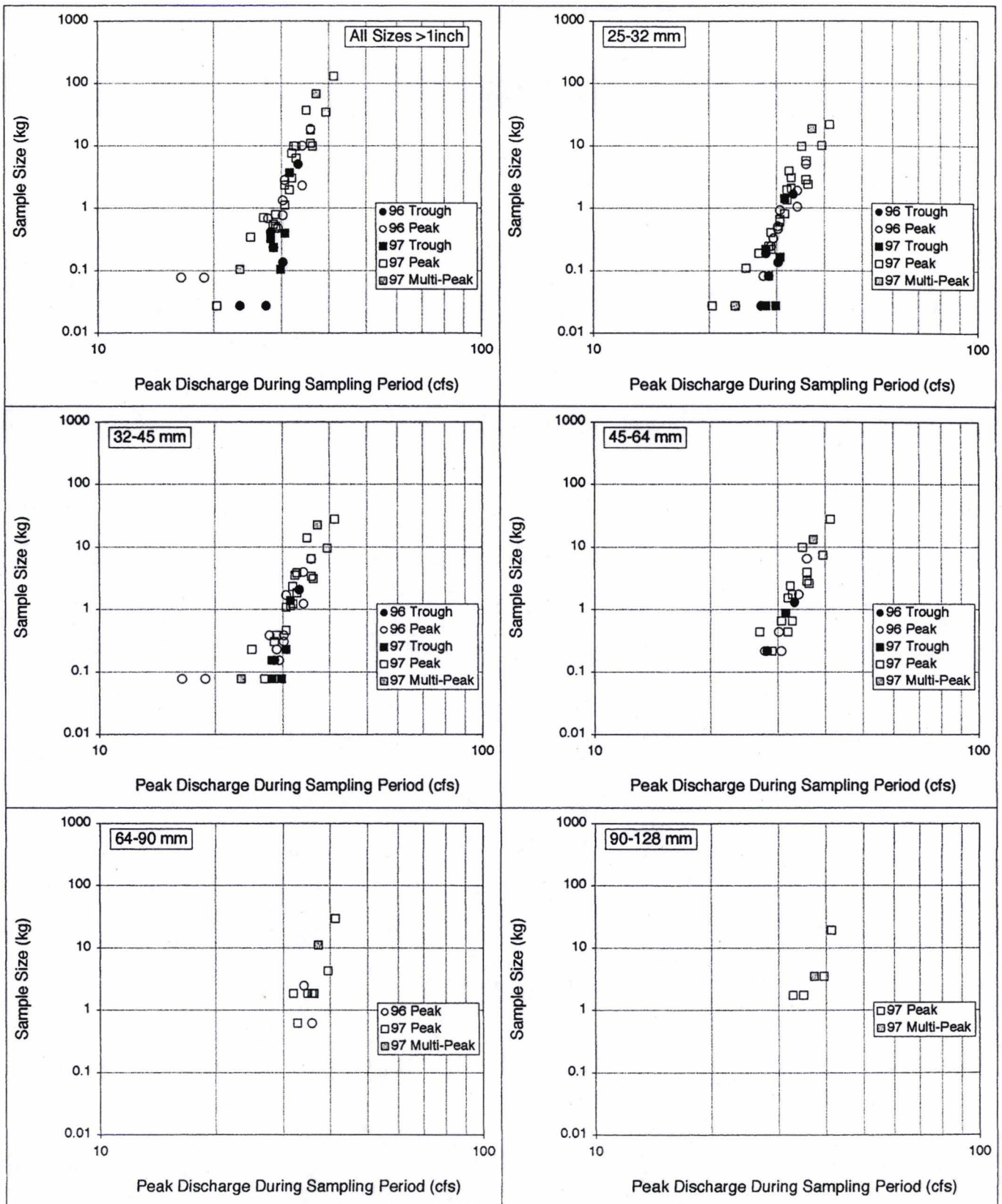


Figure 4. East St. Louis Creek, transport of sediment coarser than one inch, total sample size (kg) ESLC Basket Data, Sample Size, 4/14/00

East St. Louis Creek Basket Samples @ Weir Pond

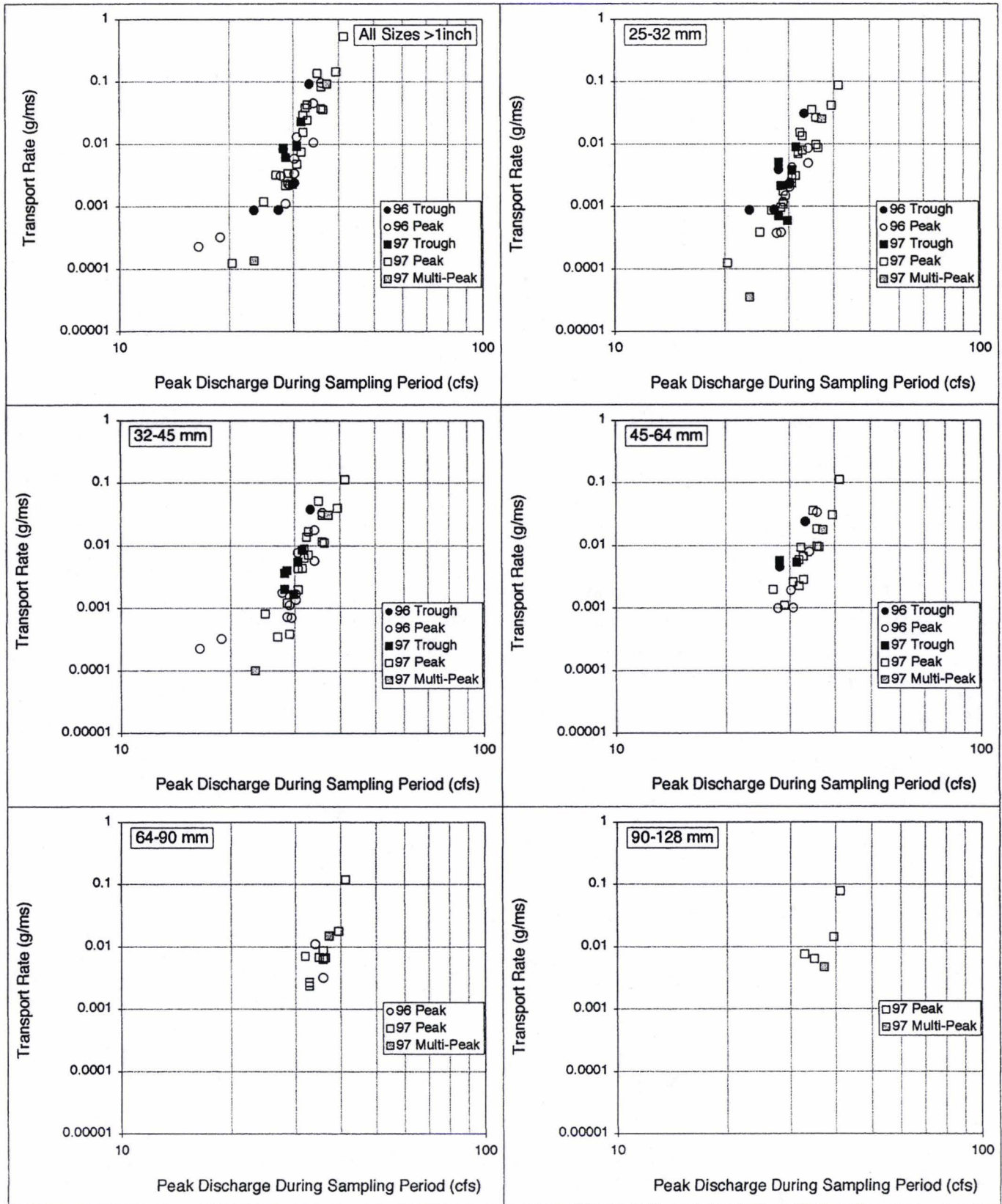


Figure 5. East St. Louis Creek, transport of sediment coarser than one inch, transport rate (g/ms) ES LC Basket Data, Sample Size, 4/14/00

Lower Fool Creek Basket Samples @ Old Weir

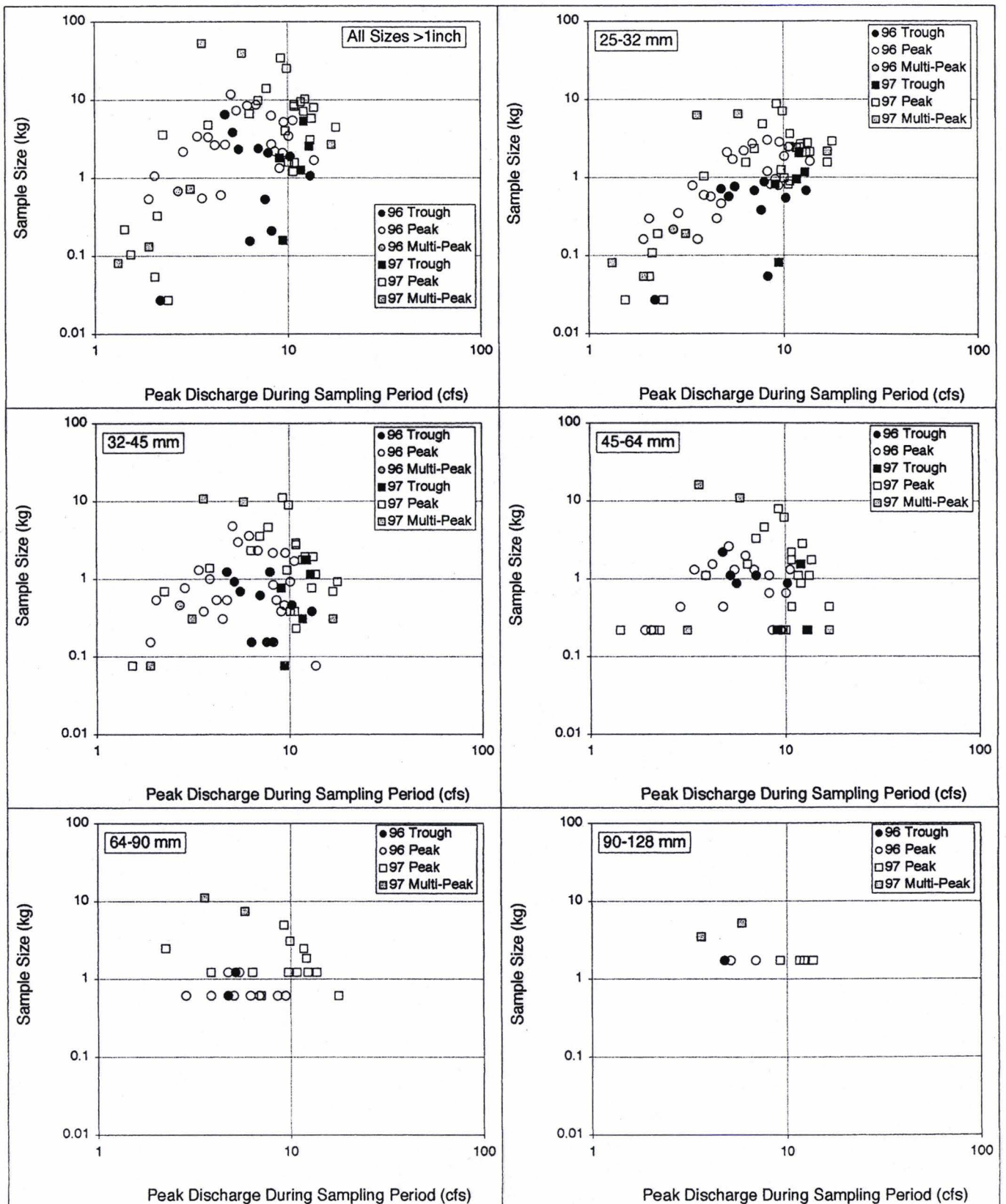


Figure 6. Lower Fool Creek, transport of sediment coarser than one inch, total sample size (kg)

Lower Fool Creek Basket Samples @ Old Weir

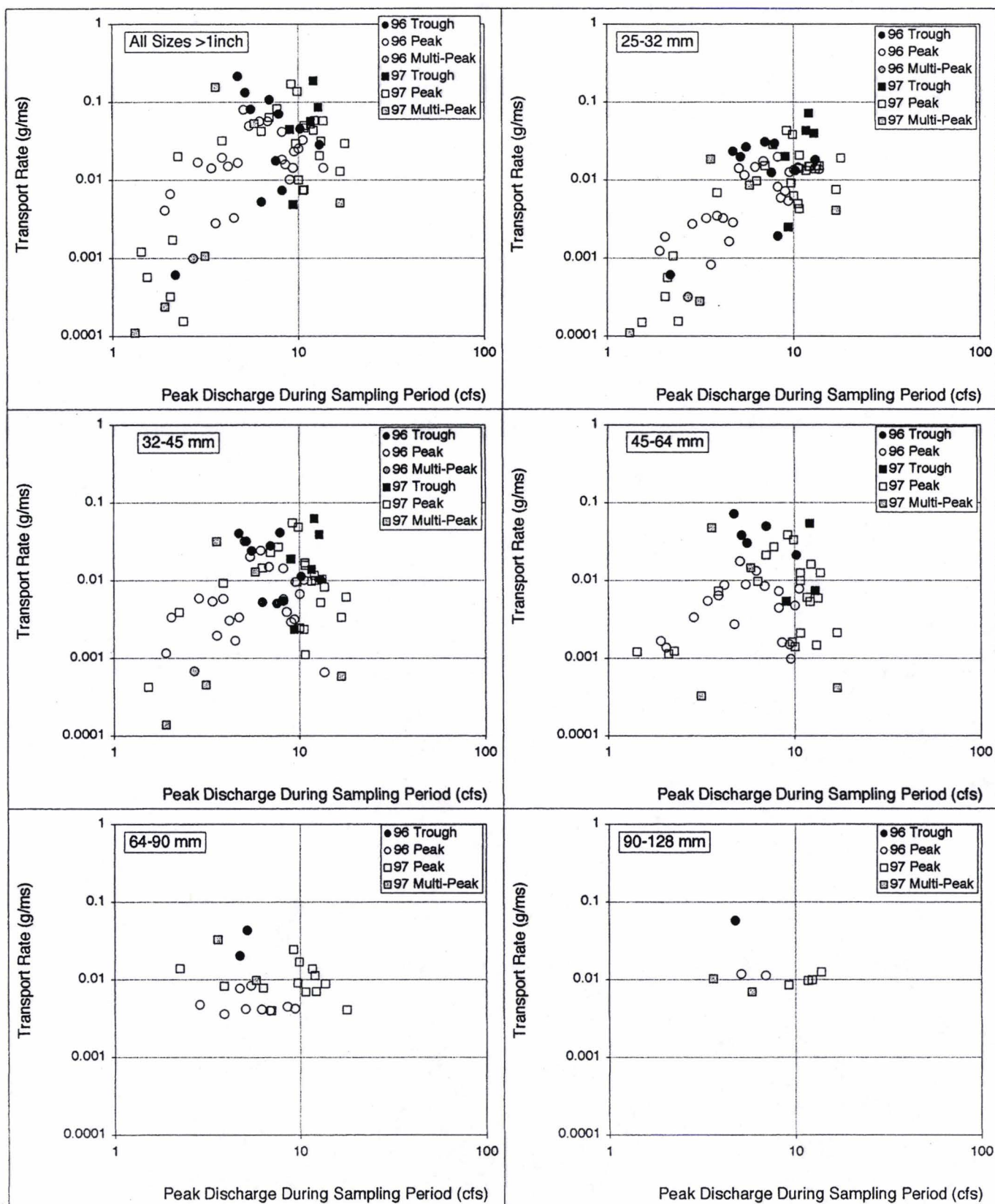


Figure 7. Lower Fool Creek, transport of sediment coarser than one inch, transport rate (g/ms)

Coon Ck. Basket Samples @ Weir Pond

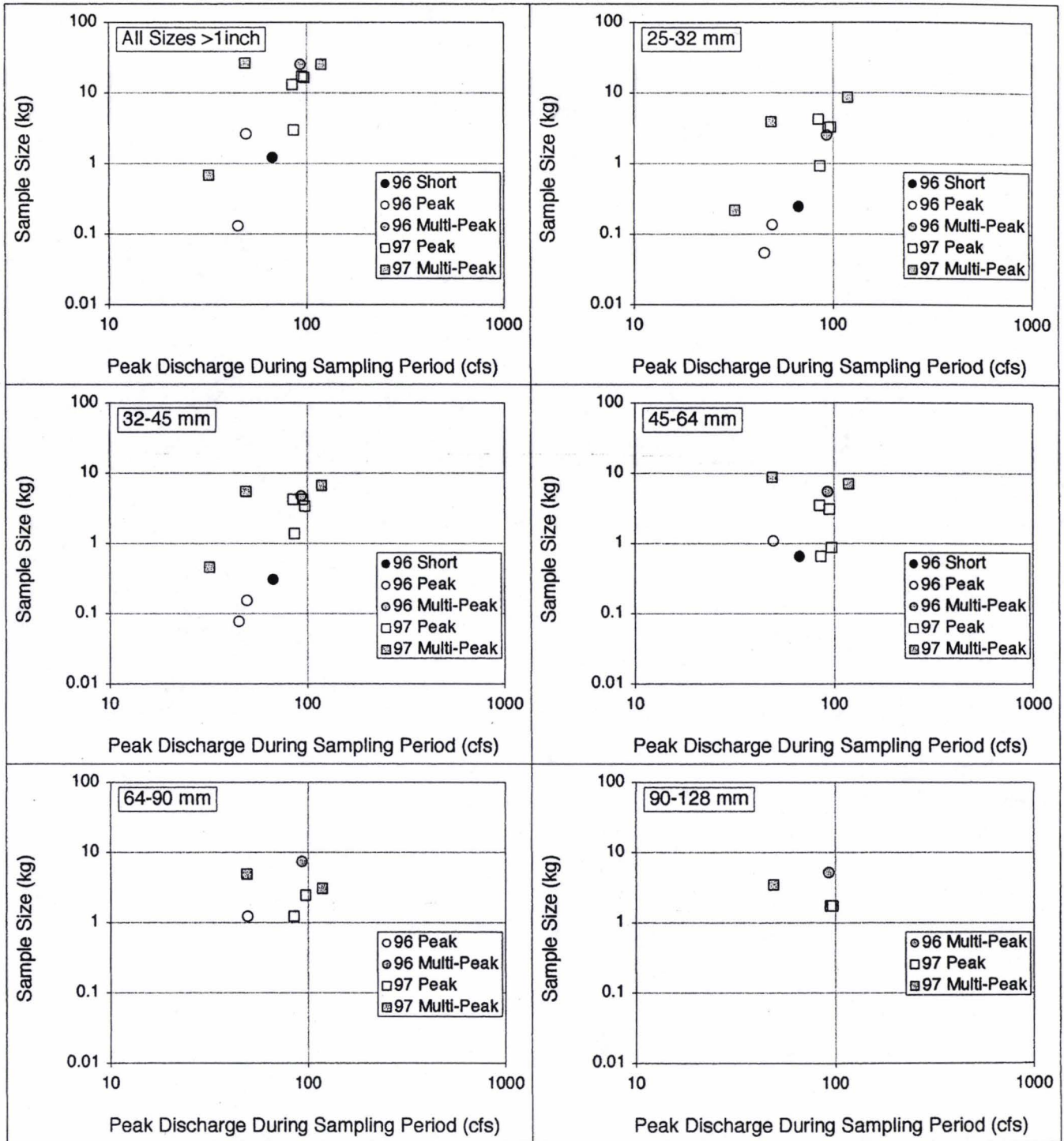


Figure 8. Coon Creek, transport of sediment coarser than one inch, total sample size (kg). Coon Qs, Sample Size, 4/14/00

Coon Ck. Basket Samples @ Weir Pond

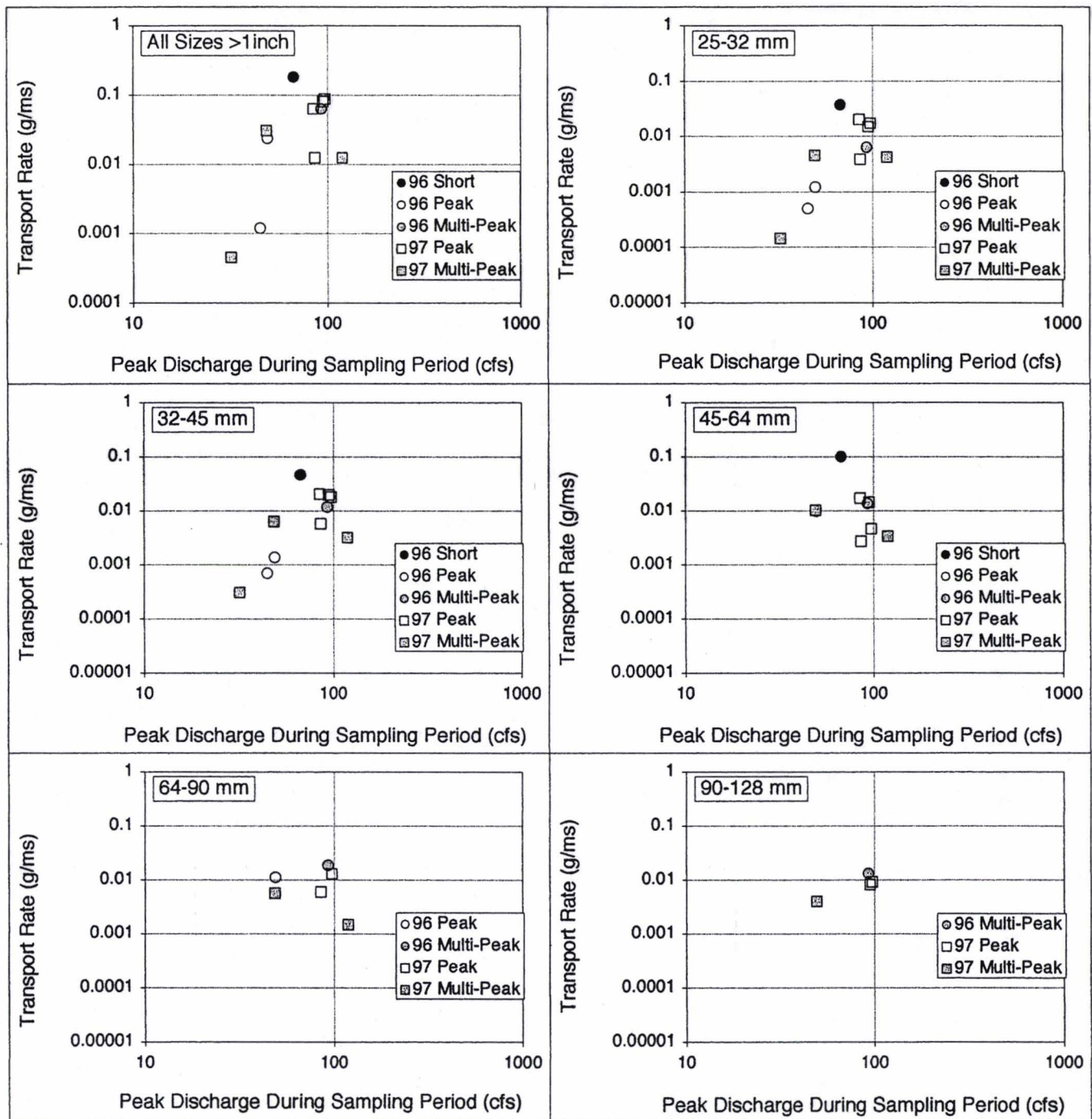
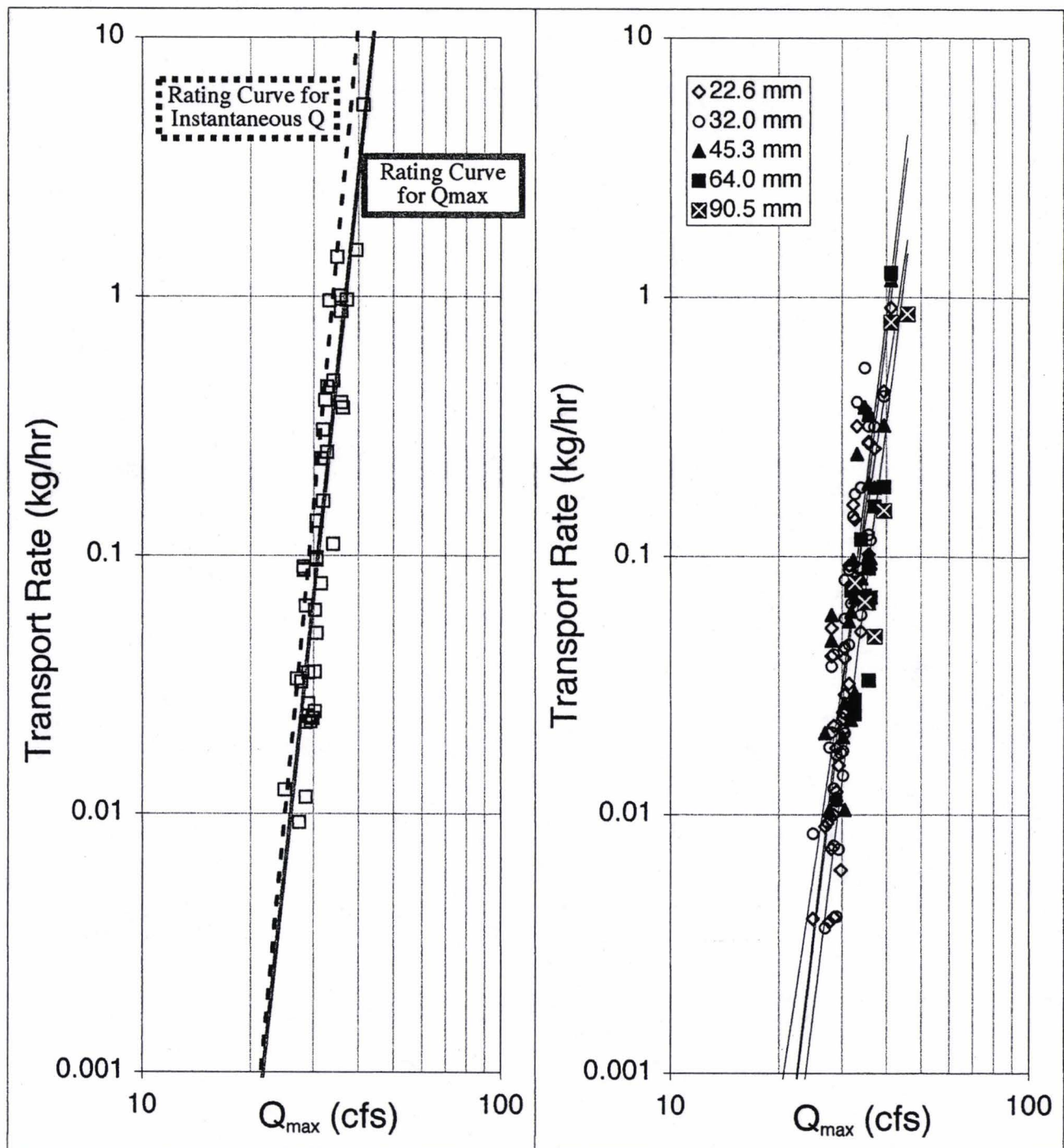


Figure 9. Coon Creek, transport of sediment coarser than one inch, total sample size (kg) Coon Ck. Sample Size, 4/14/00



Size Class	Exponent b	90% Error Bar on Exponent
22.6	11.5	1.6
32	11.6	1.8
45.3	9.3	2.3
64	11.0	4.8
90.5	8.9	11.1
All Sizes	12.7	1.8

Figure 10. East St. Louis Creek, Total and fractional transport rates.

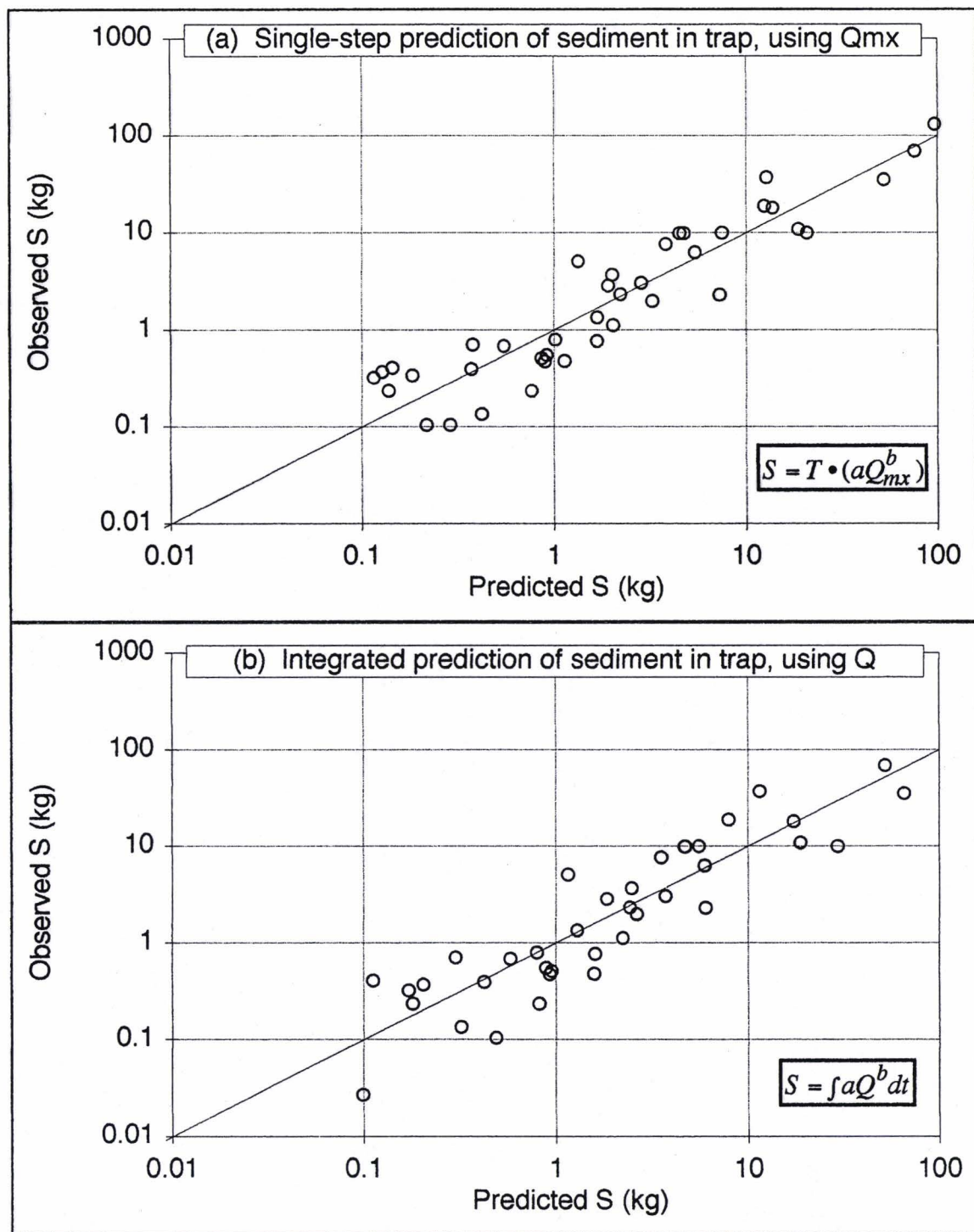


Figure 11. East St. Louis Creek, Transport correlations for Q_{max} and instantaneous discharge.

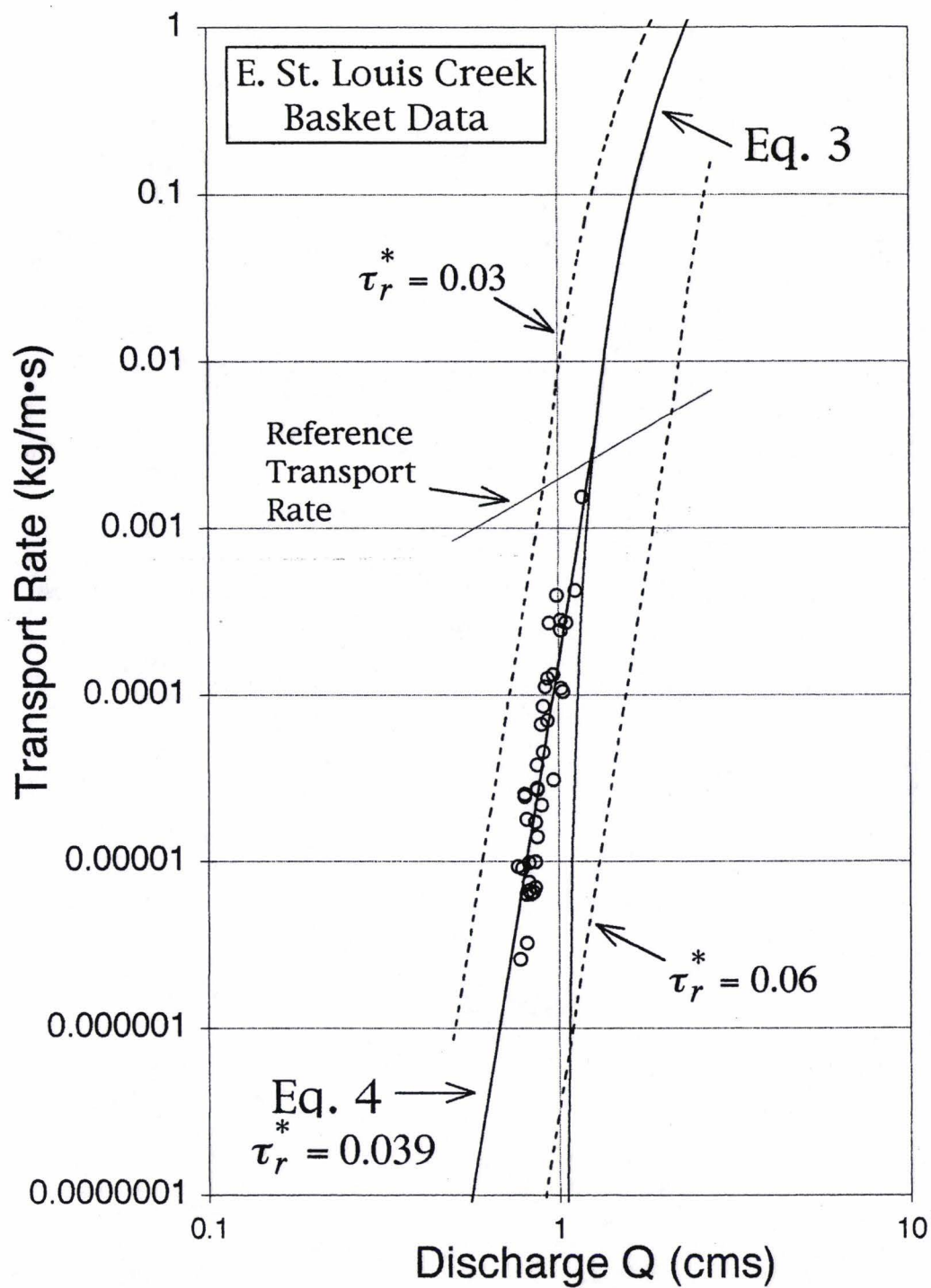


Figure 12. East St. Louis Creek. Calibrated transport model.

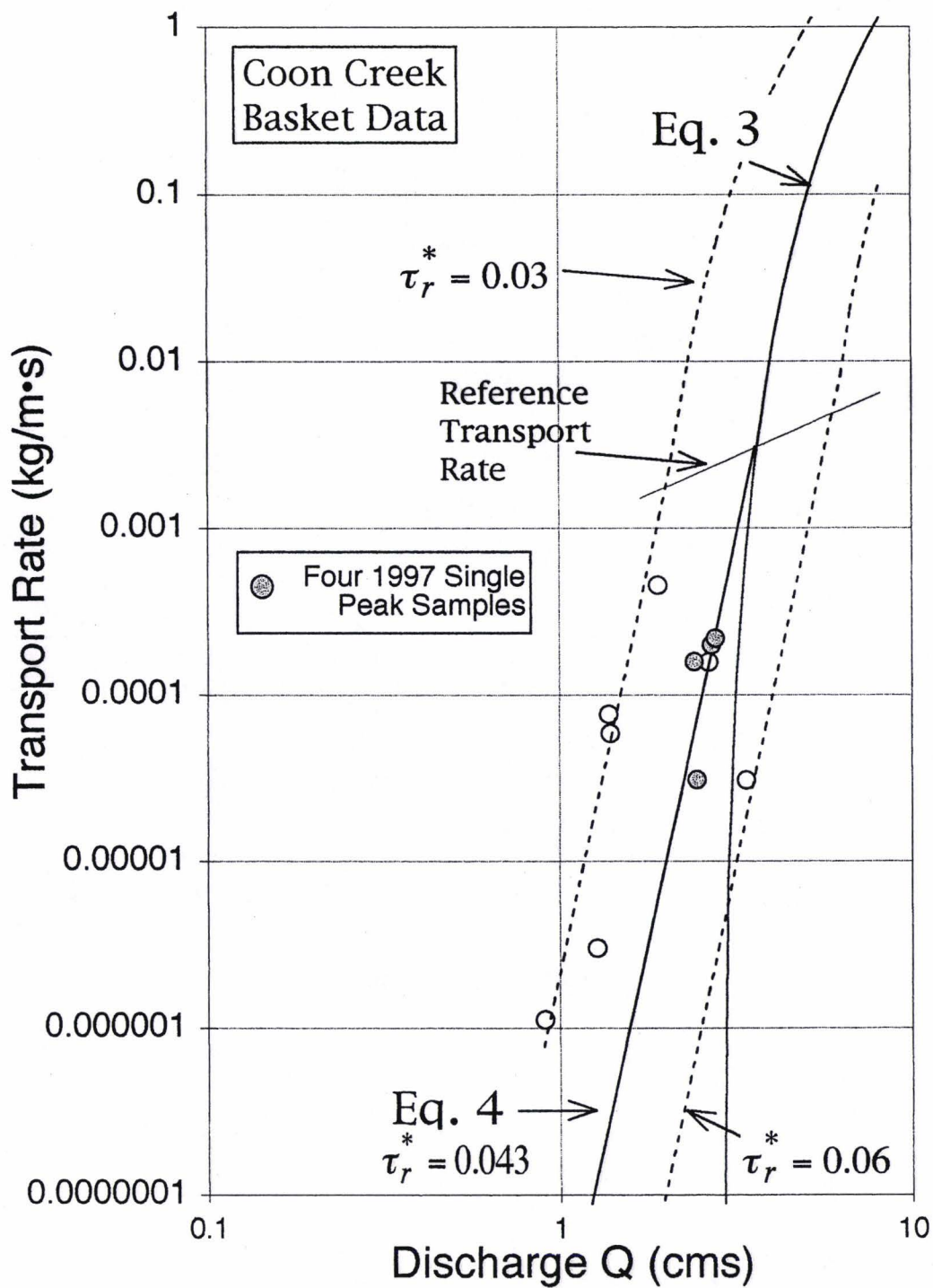


Figure 13. Coon Creek, Calibrated transport model.

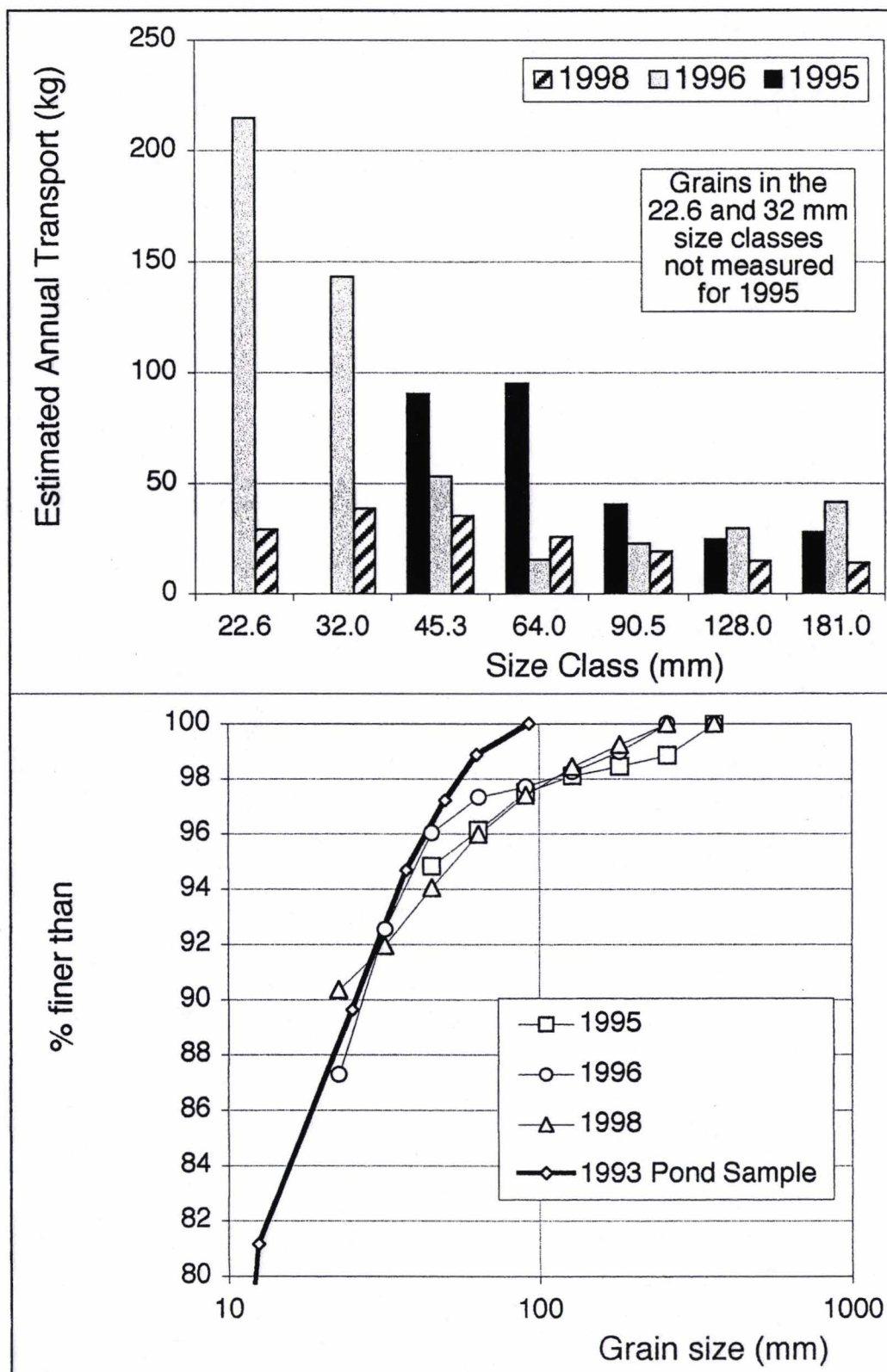


Figure 14. East St. Louis Creek, Coarse sediment in pond.

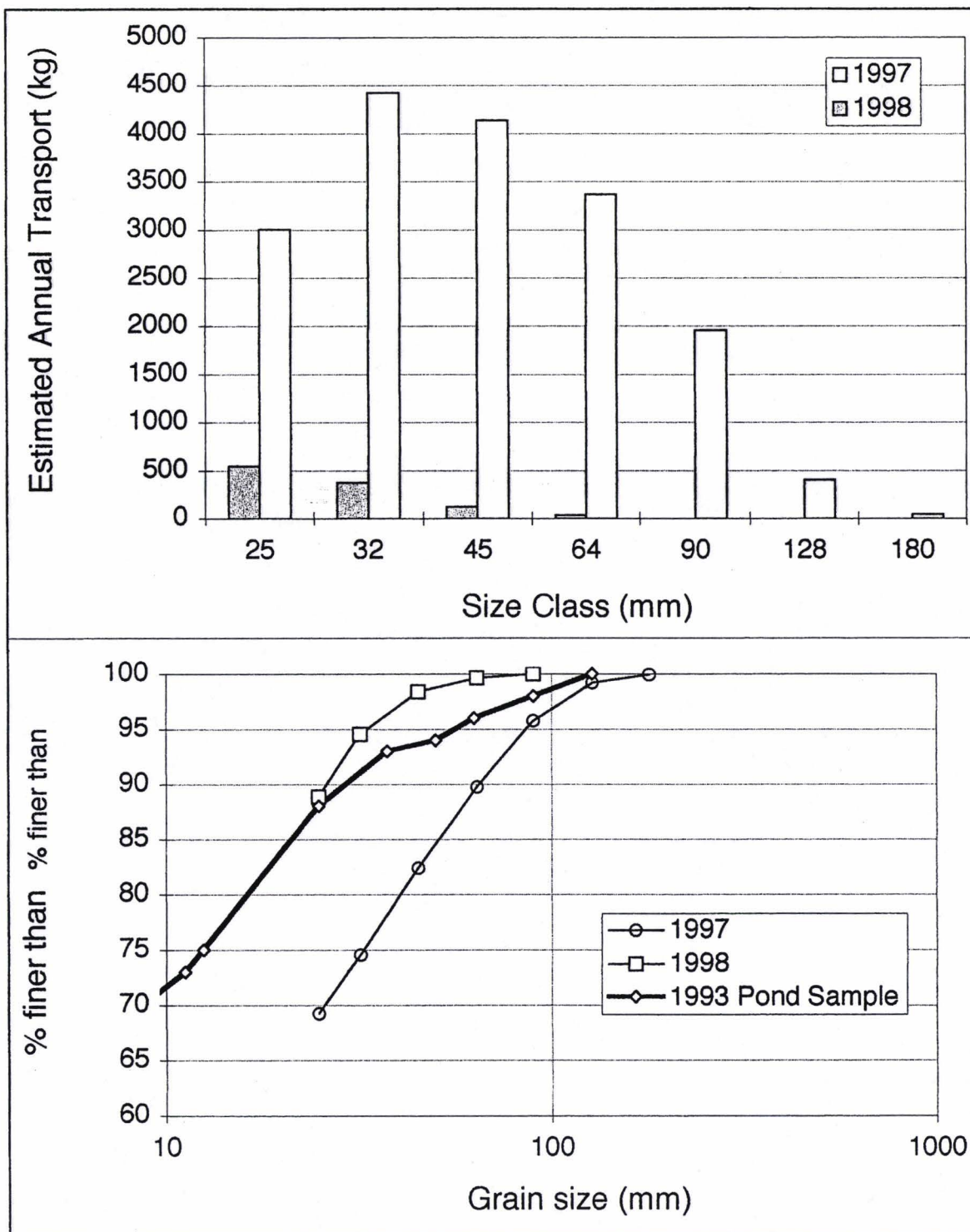


Figure 15. Coon Creek, Coarse sediment in pond.

Appendix. Table 1a. 1996 East St. Louis Creek Basket Samples									
Start	Finish	Sample	Number of grains caught on opening of size (mm):						
Date/Time	Date/Time	Duration	22.6	32	45.3	64	90.5	128	Qmax
mo./d h:min.	mo./d h:min.	(min)	(#)	(#)	(#)	(#)	(#)	(#)	(cfs)
6/14/96 11:46 AM	6/14/96 1:05 PM	79	0	0	0	0	0	0	26.94
6/14/96 1:05 PM	6/15/96 9:18 AM	1,213	3	2	0	0	0	0	28.57
6/15/96 9:21 AM	6/15/96 2:35 PM	314	62	27	6	0	0	0	33.22
6/15/96 2:39 PM	6/16/96 9:08 AM	1,109	188	84	30	1	0	0	35.85
6/16/96 9:13 AM	6/16/96 2:38 PM	325	5	0	0	0	0	0	30.23
6/16/96 2:42 PM	6/17/96 11:30 AM	1,248	34	22	1	0	0	0	30.65
6/17/96 11:30 AM	6/18/96 9:05 AM	1,295	17	4	0	0	0	0	30.23
6/18/96 9:10 AM	6/18/96 1:46 PM	276	7	0	1	0	0	0	28.16
6/18/96 1:48 PM	6/19/96 11:30 AM	1,302	19	5	2	0	0	0	30.23
6/19/96 11:35 AM	6/20/96 7:20 AM	1,185	9	3	0	0	0	0	28.98
6/20/96 7:21 AM	6/20/96 10:20 AM	179	0	0	0	0	0	0	26.13
6/20/96 10:22 AM	6/21/96 7:15 AM	1,253	12	2	0	0	0	0	29.40
6/21/96 7:16 AM	6/21/96 10:25 AM	189	0	0	0	0	0	0	27.34
6/21/96 10:25 AM	6/22/96 7:31 AM	1,266	70	51	8	4	0	0	34.09
6/22/96 7:34 AM	6/22/96 10:41 AM	187	0	0	0	0	0	0	31.50
6/22/96 10:42 AM	6/23/96 7:16 AM	1,234	39	16	0	0	0	0	34.09
6/23/96 7:20 AM	6/23/96 10:15 AM	175	1	0	0	0	0	0	27.34
6/23/96 10:15 AM	6/24/96 7:15 AM	1,260	3	5	1	0	0	0	27.75
6/24/96 7:16 AM	6/24/96 10:01 AM	165	0	0	0	0	0	0	25.34
6/24/96 10:01 AM	6/25/96 7:23 AM	1,282	0	0	0	0	0	0	25.34
6/25/96 7:23 AM	6/25/96 10:22 AM	179	1	0	0	0	0	0	23.38
6/25/96 10:23 AM	6/26/96 7:20 AM	1,257	0	0	0	0	0	0	23.38
6/26/96 7:21 AM	6/26/96 10:12 AM	171	0	0	0	0	0	0	21.86
6/26/96 10:12 AM	6/27/96 10:27 AM	1,455	0	0	0	0	0	0	23.00
6/27/96 10:27 AM	6/28/96 8:05 AM	1,298	0	0	0	0	0	0	23.00
6/28/96 8:06 AM	6/29/96 9:55 AM	1,549	0	0	0	0	0	0	21.11
6/29/96 9:56 AM	6/30/96 8:44 AM	1,368	0	1	0	0	0	0	18.91
6/30/96 8:44 AM	7/1/96 8:50 AM	1,446	0	0	0	0	0	0	18.20
7/1/96 8:50 AM	7/2/96 11:16 AM	1,586	0	0	0	0	0	0	17.15
7/2/96 11:16 AM	7/3/96 7:45 PM	1,949	0	1	0	0	0	0	16.46
7/3/96 7:46 PM	7/4/96 12:45 PM	1,019	0	0	0	0	0	0	15.78
7/4/96 12:45 PM	7/8/96 8:00 AM	5,475	0	0	0	0	0	0	17.85
7/8/96 8:00 AM	7/9/96 1:24 PM	1,764	0	0	0	0	0	0	12.83
7/9/96 1:24 PM	7/10/96 8:04 AM	1,120	0	0	0	0	0	0	11.90

Appendix. Table 1b. 1997 East St. Louis Creek Basket Samples										
Start	Finish	Sample	Number of grains caught on opening of size (mm):							
Date/Time	Date/Time	Duration	22.6	32	45.3	64	90.5	128	Qmax	
mo./d h:min.	mo./d h:min.	(min)	(#)	(#)	(#)	(#)	(#)	(#)	(cfs)	
6/4/97 8:30 AM	6/5/97 10:30 AM	1,560	358	182	45	3	1	0	34.97	
6/5/97 12:55 PM	6/6/97 9:20 AM	1,225	210	85	18	3	0	0	35.85	
6/6/97 9:30 AM	6/9/97 8:00 AM	4,230	684	293	60	18	2	0	37.20	
6/9/97 8:15 AM	6/9/97 12:40 PM	265	1	1	0	0	0	0	29.82	
6/9/97 12:40 PM	6/10/97 7:15 AM	1,115	50	16	2	0	0	0	31.93	
6/10/97 7:15 AM	6/10/97 11:20 AM	245	8	2	0	0	0	0	28.16	
6/10/97 11:20 AM	6/10/97 3:00 PM	220	3	2	0	0	0	0	28.57	
6/10/97 3:30 PM	6/11/97 7:00 AM	930	53	18	4	0	0	0	31.50	
6/11/97 7:05 AM	6/11/97 10:45 AM	220	1	1	1	0	0	0	28.16	
6/11/97 10:45 AM	6/12/97 11:25 AM	1,480	145	46	11	0	0	0	32.36	
6/12/97 11:25 AM	6/13/97 11:31 AM	1,446	22	14	3	0	0	0	30.65	
6/13/97 11:31 AM	6/14/97 9:30 AM	1,319	113	50	3	1	1	0	32.79	
6/14/97 9:30 AM	6/15/97 10:23 AM	1,493	72	30	7	3	0	0	31.93	
6/15/97 10:23 AM	6/16/97 11:33 AM	1,510	30	15	0	0	0	0	31.50	
6/16/97 11:33 AM	6/17/97 11:48 AM	1,455	9	4	0	0	0	0	28.57	
6/17/97 11:48 AM	6/18/97 6:50 AM	1,142	8	1	1	0	0	0	28.98	
6/18/97 6:50 AM	6/19/97 7:50 AM	1,500	77	24	8	1	0	0	32.79	
6/19/97 7:50 AM	6/19/97 11:50 AM	240	6	3	0	0	0	0	30.65	
6/19/97 11:50 AM	6/20/97 11:30 AM	1,420	802	362	127	48	11	1	41.32	
6/20/97 1:10 PM	6/21/97 12:10 PM	1,380	371	125	34	7	2	0	39.47	
6/21/97 12:10 PM	6/22/97 2:40 PM	1,590	88	40	12	3	0	0	36.30	
6/22/97 2:50 PM	6/23/97 6:40 PM	1,670	105	44	13	3	0	0	35.85	
6/23/97 6:50 PM	6/24/97 5:00 PM	1,330	24	6	0	0	0	0	30.65	
6/24/97 5:05 PM	6/25/97 3:30 PM	1,345	15	5	0	0	0	0	28.98	
6/25/97 3:30 PM	6/26/97 12:30 PM	1,260	7	1	2	0	0	0	26.94	
6/26/97 12:30 PM	6/27/97 3:45 PM	1,635	4	3	0	0	0	0	24.94	
6/27/97 3:45 PM	6/30/97 5:00 PM	4,395	1	1	0	0	0	0	23.38	
6/30/97 5:00 PM	7/1/97 2:00 PM	1,260	1	0	0	0	0	0	20.37	
7/1/97 2:00 PM	7/3/97 11:30 AM	2,730	0	0	0	0	0	0	18.56	
7/3/97 11:30 AM	7/7/97 7:45 AM	5,535	0	0	0	0	0	0	16.12	
7/7/97 7:45 AM	7/9/97 7:15 AM	2,850	0	0	0	0	0	0	13.47	
7/9/97 7:15 AM	7/11/97 8:00 AM	2,925	0	0	0	0	0	0	12.52	
7/11/97 8:00 AM	7/14/97 10:00 AM	4,440	0	0	0	0	0	0	11.29	
7/14/97 10:00 AM	7/15/97 10:45 AM	1,485	0	0	0	0	0	0	9.81	
7/15/97 10:45 AM	7/16/97 11:15 AM	1,470	0	0	0	0	0	0	9.52	
7/16/97 11:15 AM	7/17/97 9:30 AM	1,335	0	0	0	0	0	0	9.52	
7/17/97 9:30 AM	7/21/97 12:30 PM	5,940	0	0	0	0	0	0	9.24	
7/21/97 12:30 PM	7/22/97 11:30 AM	1,380	0	0	0	0	0	0	7.86	
7/22/97 11:30 AM	7/23/97 11:30 AM	1,440	0	0	0	0	0	0	7.60	
7/23/97 11:30 AM	7/24/97 11:30 AM	1,440	0	0	0	0	0	0	9.24	

Appendix. Table 2a. 1996 Fool Creek Basket Samples										
Start	Finish	Sample	Number of grains caught on opening of size (mm):							
Date/Time	Date/Time	Duration	22.6	32	45.3	64	90.5	128	181	Qmax
mo./d h:min.	mo./d h:min.	(min)	(#)	(#)	(#)	(#)	(#)	(#)	(#)	(cfs)
6/14/96 4:48 PM	6/15/96 11:22 AM	1,114	69	12	3	0	0	0	0	10.08
6/15/96 11:29 AM	6/15/96 4:33 PM	304	25	5	0	0	0	0	0	13.14
6/15/96 4:44 PM	6/16/96 8:35 AM	951	59	1	0	0	0	0	0	13.77
6/16/96 8:41 AM	6/16/96 2:15 PM	334	20	6	4	0	0	0	0	10.26
6/16/96 2:19 PM	6/17/96 12:55 PM	1,356	90	22	6	0	0	0	0	10.62
6/17/96 1:00 PM	6/18/96 7:15 PM	1,815	104	28	1	0	0	0	0	9.56
6/18/96 7:17 PM	6/19/96 1:03 PM	1,066	35	5	0	0	0	0	0	9.06
6/19/96 1:05 PM	6/20/96 7:35 AM	1,110	30	7	1	1	0	0	0	8.57
6/20/96 7:38 AM	6/20/96 11:39 AM	241	32	16	0	0	0	0	0	7.94
6/20/96 11:40 AM	6/21/96 7:32 AM	1,192	44	11	3	0	0	0	0	8.25
6/21/96 7:35 AM	6/21/96 11:41 AM	246	14	2	0	0	0	0	0	7.64
6/21/96 11:40 AM	6/22/96 7:20 AM	1,180	29	6	1	1	0	0	0	9.39
6/22/96 7:24 AM	6/22/96 11:14 AM	230	2	2	0	0	0	0	0	8.25
6/22/96 11:16 AM	6/23/96 7:31 AM	1,215	110	28	5	0	0	0	0	8.25
6/23/96 7:36 AM	6/23/96 10:35 AM	179	25	8	5	0	0	0	0	7.06
6/23/96 10:36 AM	6/24/96 7:29 AM	1,253	100	30	6	1	1	0	0	6.91
6/24/96 7:31 AM	6/24/96 11:27 AM	236	0	2	0	0	0	0	0	6.36
6/24/96 11:28 AM	6/25/96 7:37 AM	1,209	81	47	9	1	0	0	0	6.23
6/25/96 7:41 AM	6/25/96 11:35 AM	234	28	9	4	0	0	0	0	5.59
6/25/96 11:37 AM	6/26/96 7:37 AM	1,200	63	39	6	2	0	0	0	5.46
6/26/96 7:41 AM	6/26/96 11:34 AM	233	21	12	5	2	0	0	0	5.22
6/26/96 11:38 AM	6/27/96 7:37 AM	1,199	77	62	12	1	1	0	0	5.10
6/27/96 7:41 AM	6/27/96 11:47 AM	246	26	16	10	1	1	0	0	4.76
6/27/96 11:48 AM	6/28/96 9:30 AM	1,302	17	7	2	2	0	0	0	4.76
6/28/96 9:32 AM	6/29/96 10:21 AM	1,489	11	4	0	0	0	0	0	4.53
6/29/96 10:22 AM	6/30/96 10:06 AM	1,424	21	7	7	0	0	0	0	4.21
6/30/96 10:08 AM	7/1/96 9:16 AM	1,388	22	13	5	1	0	0	0	3.90
7/1/96 9:19 AM	7/2/96 11:49 AM	1,590	6	5	0	0	0	0	0	3.61
7/2/96 11:49 AM	7/3/96 8:27 PM	1,958	29	17	6	0	0	0	0	3.42
7/3/96 8:30 PM	7/4/96 2:00 PM	1,050	13	10	2	1	0	0	0	2.89
7/4/96 2:00 PM	7/8/96 9:55 AM	5,515	8	6	0	0	0	0	0	2.72
7/8/96 9:56 AM	7/8/96 3:57 PM	361	1	0	0	0	0	0	0	2.19
7/8/96 3:57 PM	7/9/96 1:32 PM	1,295	11	7	1	0	0	0	0	2.05
7/9/96 1:34 PM	7/9/96 3:56 PM	142	0	0	0	0	0	0	0	1.98
7/9/96 3:56 PM	7/10/96 9:41 AM	1,065	6	2	1	0	0	0	0	1.91

Appendix. Table 2b. 1997 Fool Creek Basket Samples										
Start	Finish	Sample	Number of grains caught on opening of size (mm):							
Date/Time	Date/Time	Duration	22.6	32	45.3	64	90.5	128	181	Qmax
mo./d h:min.	mo./d h:min.	(min)	(#)	(#)	(#)	(#)	(#)	(#)	(#)	(cfs)
6/4/97 10:15 AM	6/5/97 2:05 PM	1,670	57	9	2	0	0	0	0	16.93
6/5/97 2:25 PM	6/6/97 10:50 AM	1,225	106	12	0	1	0	0	0	17.91
6/6/97 11:00 AM	6/9/97 10:05 AM	4,265	79	4	1	0	0	0	0	16.93
6/9/97 10:20 AM	6/9/97 2:20 PM	240	43	15	1	0	0	0	0	12.94
6/9/97 2:20 PM	6/10/97 9:10 AM	1,130	78	15	8	2	1	0	0	13.77
6/10/97 9:15 AM	6/10/97 1:05 PM	230	75	23	7	0	0	0	0	12.14
6/10/97 1:10 PM	6/11/97 9:15 AM	1,205	76	10	1	0	0	0	0	13.14
6/11/97 9:15 AM	6/11/97 12:15 PM	180	35	4	0	0	0	0	0	11.75
6/11/97 12:15 PM	6/12/97 1:15 PM	1,500	102	25	5	0	0	0	0	13.35
6/12/97 1:15 PM	6/13/97 1:04 PM	1,429	98	23	13	2	1	0	0	12.33
6/13/97 1:04 PM	6/14/97 11:16 AM	1,332	90	25	4	3	0	0	0	12.14
6/14/97 11:16 AM	6/15/97 11:40 AM	1,464	88	23	5	4	1	0	0	11.75
6/15/97 11:40 AM	6/16/97 11:15 AM	1,415	133	38	10	0	0	0	0	10.80
6/16/97 11:15 AM	6/17/97 11:06 AM	1,431	91	36	8	2	0	0	0	10.80
6/17/97 11:06 AM	6/18/97 8:15 AM	1,269	36	5	1	0	0	0	0	10.08
6/18/97 8:18 AM	6/18/97 1:48 PM	330	30	10	1	0	0	0	0	9.06
6/18/97 1:50 PM	6/19/97 8:15 AM	1,105	46	17	1	2	0	0	0	9.74
6/19/97 8:15 AM	6/19/97 12:40 PM	265	3	1	0	0	0	0	0	9.39
6/19/97 12:40 PM	6/20/97 4:45 PM	1,685	33	3	2	0	0	0	0	10.80
6/20/97 4:50 PM	6/21/97 2:50 PM	1,320	30	5	0	0	0	0	0	10.62
6/21/97 2:50 PM	6/22/97 3:35 PM	1,485	258	116	28	5	0	0	0	9.91
6/22/97 3:50 PM	6/23/97 7:15 PM	1,645	321	145	36	8	1	0	0	9.23
6/23/97 7:30 PM	6/24/97 6:30 PM	1,380	177	60	21	0	0	0	0	7.79
6/24/97 6:40 PM	6/25/97 3:30 PM	1,250	86	46	15	1	0	0	0	7.06
6/25/97 3:35 PM	6/26/97 1:00 PM	1,285	57	30	7	2	0	0	0	6.36
6/26/97 1:05 PM	6/30/97 6:45 PM	6,100	238	127	50	12	3	0	0	5.84
6/30/97 7:00 PM	7/1/97 3:15 PM	1,215	38	18	5	2	0	0	0	3.90
7/1/97 3:15 PM	7/3/97 1:00 PM	2,745	230	139	74	18	2	1	0	3.61
7/3/97 1:15 PM	7/7/97 8:30 AM	5,475	7	4	1	0	0	0	0	3.15
7/7/97 8:30 AM	7/8/97 8:00 AM	1,410	1	0	0	0	0	0	0	2.41
7/8/97 8:00 AM	7/9/97 8:00 AM	1,440	7	9	1	4	0	0	0	2.26
7/9/97 8:00 AM	7/10/97 10:00 AM	1,560	4	0	1	0	0	0	0	2.12
7/10/97 10:00 AM	7/11/97 8:45 AM	1,365	2	0	0	0	0	0	0	2.05
7/11/97 8:45 AM	7/14/97 11:30 AM	4,485	2	1	0	0	0	0	0	1.91
7/14/97 11:30 AM	7/15/97 12:00 PM	1,470	1	1	0	0	0	0	0	1.54
7/15/97 12:00 PM	7/16/97 12:30 PM	1,470	0	0	1	0	0	0	0	1.43
7/16/97 12:30 PM	7/17/97 10:45 AM	1,335	0	0	0	0	0	0	0	1.37
7/17/97 10:45 AM	7/21/97 2:15 PM	5,970	3	0	0	0	0	0	0	1.32
7/21/97 2:15 PM	7/22/97 12:15 PM	1,320	0	0	0	0	0	0	0	1.07
7/22/97 12:15 PM	7/23/97 12:15 PM	1,440	0	0	0	0	0	0	0	1.07
7/23/97 12:15 PM	7/24/97 12:15 PM	1,440	0	0	0	0	0	0	0	1.37

Appendix. Table 3. 1996 and 1997 Coon Creek Basket Samples											
Start	Finish	Sample	Number of grains caught on opening of size (mm):								
Date/Time	Date/Time	Duration	22.6	32	45.3	64	90.5	128	181	NOTES	Qmax
mo./d h:min.	mo./d h:min.	(min)	(#)	(#)	(#)	(#)	(#)	(#)	(#)		(cfs)
6/20/96 2:50 PM	6/20/96 4:20 PM	90	9	4	3	0	0	0	0	1 basket	66.96
6/20/96 4:30 PM	6/24/96 11:15 AM	5,445	93	61	25	12	3	0	0	1 basket	92.98
6/24/96 11:15 AM	6/25/96 12:35 PM	1,520	5	2	5	2	0	0	0	1 basket	49.16
6/25/96 12:35 PM	6/26/96 1:20 PM	1,485	2	1	0	0	0	0	0	1 basket	44.89
6/26/96 1:20 PM	6/27/96 1:40 PM	1,460	0	0	0	0	0	0	0	1 basket	47.25
6/27/96 1:40 PM	7/1/96 2:00 PM	5,780	0	0	0	0	0	0	0	1 basket	40.29
7/1/96 2:00 PM	7/3/96 10:25 AM	2,665	0	0	0	0	0	0	0	1 basket	24.82
6/13/97 12:15 PM	6/14/97 9:50 AM	1,295	121	44	4	4	1	1	0	2 baskets	97.19
6/14/97 10:20 AM	6/15/97 10:40 AM	1,460	119	55	14	0	1	1	0	2 baskets	94.78
6/15/97 11:15 AM	6/16/97 10:50 AM	1,415	156	55	16	2	0	0	0	2 baskets	84.76
6/16/97 11:05 AM	6/17/97 2:20 PM	1,635	34	18	3	0	0	0	0	2 baskets	85.92
6/17/97 2:40 PM	6/27/97 9:00 AM	14,060	321	86	32	5	0	0	0	2 baskets	119.11
6/27/97 9:30 AM	7/1/97 12:00 PM	5,910	144	71	40	8	2	0	0	2 baskets	48.68
7/1/97 12:30 PM	7/8/97 3:50 PM	10,280	8	6	0	0	0	0	0	2 baskets	32.04
7/8/97 3:50 PM	7/16/97 12:55 PM	11,345	0	0	0	0	0	0	0	2 baskets	22.92